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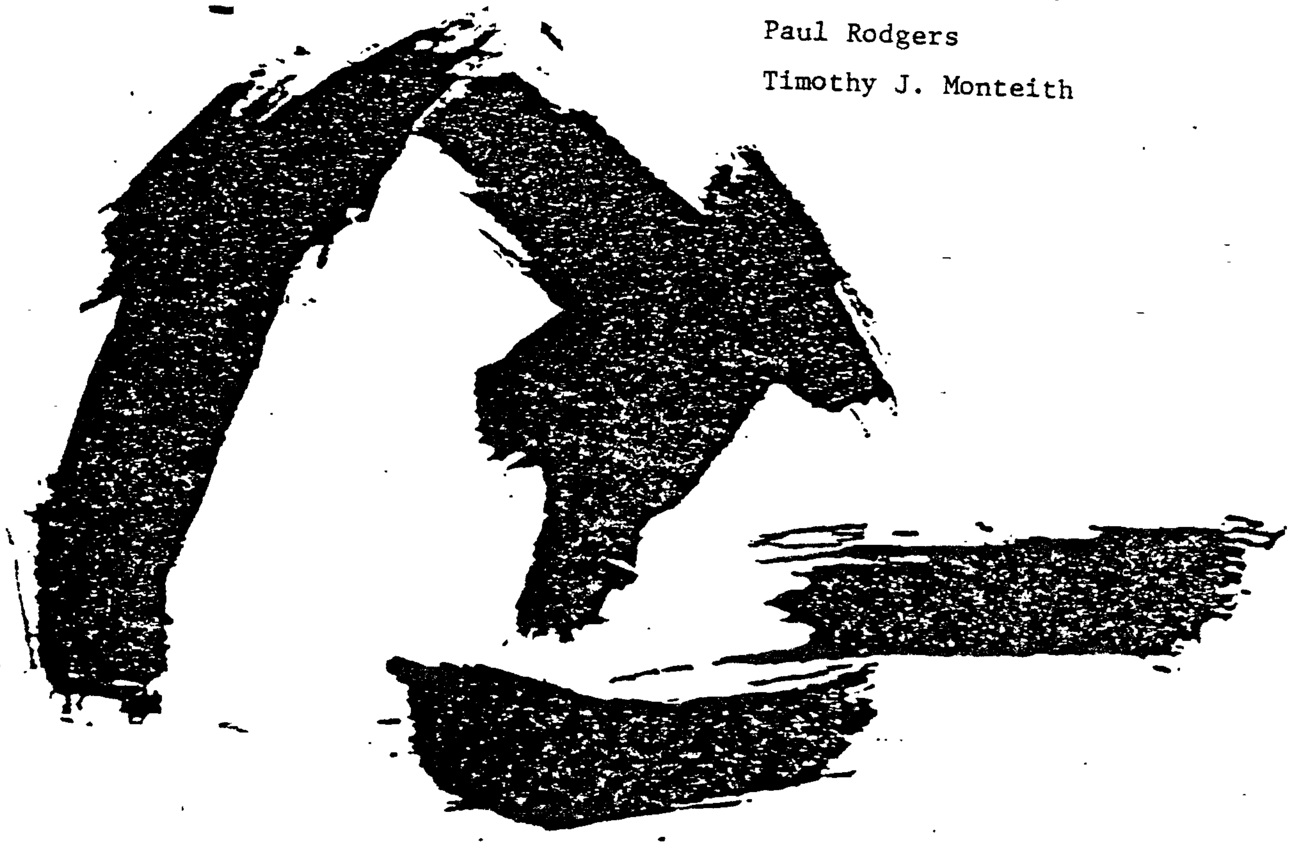

Great Lakes Environmental Planning Study (GLEPS)
Great Lakes Basin Commission, Ann Arbor, Michigan 48106
Contribution No. 39
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[1]Great Lakes Environmental Research Laboratory
National Oceanic and Atmospheric Administration
Ann Arbor, MI 48104
(GLERL Contribution No. 272)

[2]Large Lakes Research Station
U.S. Environmental Protection Agency
Grosse Isle, MI 48138

[3]Great Lakes Basin Commission

ABSTRACT

Concentrations of chloride and other conservative ions in the Great Lakes are of interest, not only as indicators of pollution, but also because these ions may affect species diversity of algae and other aquatic organisms. As part of an evaluation of the current status of conservative ions in the lakes, a current chloride budget was developed and its implications assessed. Chloride inputs to the lakes (in 10^6 MT/YR) increase in the order of Superior (0.3), Michigan (0.9), Huron (1.1), Erie (3.7), and Ontario (6.3). The Oswego River, draining into Lake Ontario, contributes more chloride than any other U.S. tributary. Regarding specific sources, discharges from industrial processes are probably the most significant. Road salt contributes an important, but not necessarily predominant, portion of the anthropogenic load to the lakes. Overall, chloride inputs, especially industrial discharges, appear to have decreased in recent years. Lake Erie in-lake chloride concentrations have, in fact, decreased measurably compared to those in the early 1960's.

Based on a chloride model that treats the lakes as five completely mixed systems in series, it is estimated that, if current loads are maintained, the average chloride concentrations in Lake Michigan should increase over the long term from less than 8 mg/L to nearly 20 mg/L. Chloride concentrations in the other Great Lakes are predicted to remain relatively stable. Based on analogies to other lakes where chloride levels have increased, it is uncertain whether the expected rise in the chloride concentrations in Lake Michigan will result in a shift in phytoplankton toward more nuisance species. It may well be that increased conservative ion levels are a factor ecologically, but of less importance than other factors,

such as nutrients. The response of the Great Lakes to the massive phosphorus reduction program of the 1970's should provide further insight into the relative importance of chloride and other conservative ions as pollutants.

INTRODUCTION

Chloride has long been used as a tracer of pollution (Beeton, 1965; Upchurch, 1976), but has only recently been implicated as a pollutant itself in the Great Lakes, the worlds largest freshwater resource. The concern over chloride (and other conservative ions) stems from its possible role in changing the species diversity and distribution of algae and other organisms in the Great Lakes.

Concern over chloride is exemplified by a recent conference held to help develop a five year federal plan for research and development in the Great Lakes. Chloride discharges, which have increased markedly over the last century, were identified as one of several major problems worthy of special attention (Beeton et al., 1980).

In response to renewed interest in chloride, this paper summarizes current information on chloride inputs to the Great Lakes from various sources. Chloride trends in the lakes are then evaluated with the aid of two mathematical models. Finally, management implications of current and future chloride inputs to the lakes are discussed. Particular attention is given to Lake Michigan, especially with regard to modeling the response of lakes to chloride inputs.

Chloride Sources

Chloride sources include land runoff, base flow (i.e., ground water inputs), municipal and industrial effluents, the atmosphere and several minor contributers. In the developed portion of the Great Lakes basin, point sources and runoff from agricultural and urban land dominate chloride sources, while in the undeveloped portion, which includes most of the Superior and Huron watersheds and part of Michigan's basin, chloride inputs are mostly derived from natural weathering of chloride containing minerals.

Because of its local availability (large underground deposits within the basin provide an abundant supply of salt), sodium chloride is commonly used for road deicing in the Great Lakes basin. Salt use has proliferated in recent years as a "bare pavement policy" has been in force in many urban areas. Highway runoff may enter tributaries directly or may enter tributaries via storm sewers (separate or combined) and can result in chloride concentrations as high as 10,000 mg/L (Schraufnagel, 1965).

One portion of the Great Lakes that has been acutely affected by road salt runoff is Irondequoit Bay, a small embayment near Rochester, N.Y., that is separated from Lake Ontario by a sandbar. Over the past 20 years road-salt runoff to the bay has resulted in an increase in the chloride level to the point that the drinking water standard of 250 mg/L has been exceeded (Bubeck et al., 1971). Further, a vertical density gradient has formed which has impeded mixing of the bay, particularly during spring and fall turnover. It is speculated that continued road salt buildup may eventually cause the bay to become meromictic (Bannister and Bubeck, 1978). Although Irondequoit Bay is a dramatic example of road salt pollution of a Great Lakes embayment, it is perhaps a unique case due to the very limited mixing between the bay and Lake Ontario proper.

The Pollution from Land Use Activities Reference Group (PLUARG, 1977) estimated that about 2.8 x 10^6 metric tons of chloride are currently applied to roads in the Great Lakes basin annually. However, due to (1) increasing salt prices, (2) concern over salt induced corrosion, (3) local water quality problems caused by salt runoff and (4) damage to terrestrial vegetation, the rate of salt application will probably decline (PLUARG 1977, 1978). Importantly, the Pollution from Land Use Activities Reference Group Study (PLUARG, 1978) concluded that, given the current and expected future use of chloride for deicing, road salt pollution was more of a local problem than a Great Lakes problem.

Base Flow

Ground water inputs to streams (i.e., base flow) are also a source of chloride in tributaries. In some areas groundwater chloride concentrations can be high, particularly in deeper bedrock deposits. Cummings (1980) reported the results of a survey of the chemical characteristics of groundwater deposits within Michigan and found that bedrock deposits had a mean concentration of 71 mg/L while glacial (surface) deposits had a mean concentration of 11 mg/L. Ground water contributions to streams would likely be from surface deposits, and thus high chloride levels in streams are not generally the result of groundwater inputs (Sonzogni et al., 1978).

Point Sources

Municipal sewage effluent contains substantial amounts of chloride. Conventional treatment processes do not remove chloride to an appreciable extent. Typical chloride concentrations in municipal effluents of plants draining into the Great Lakes range from 50 mg/L or less to over 160 mg/L. Major sources of chloride received by treatment plants include human wastes, garbage disposal wastes, water softening by-products, urban runoff (for combined sewer systems) and industrial contributions. Humans contribute about 6 g of chloride per person per day to sewage (Metcalf and Eddy, 1972). Home water softening systems, where numerous, can be responsible for large chloride inputs to wastewater (Schraufnagel, 1965).

Whereas most municipal waste treatment processes do not remove chloride, chemical treatment practices may actually add chloride to effluents. Over the last ten years phosphorus removal processes, largely in the form of chemical precipitation have been implemente at a large number of municipal sewage treatment plants in the Great Lakes basin. Of the chemicals added to wastewater for phosphorus removal, ferric chloride is most frequently used (Monteith et al., 1980). Since chloride is a by-product of ferric chloride use, this phosphorus removal practice appears to be adding to the chloride content of discharge water. For example, Kenaga (1978) noted that the chloride concentration in Lansing, Michigan, wastewater effluent increased about 10 mg/L as a result of phosphorus removal. Consequently, phosphorus removal may be contributing measurably to chloride inputs.

Discharges from industrial processes are probably the most significant of all chloride sources to the Great Lakes. Chemical, steel and food packaging industries are major sources. A number of industries have located in the basin not only because of the abundance of water, but also because of the large salt deposits found in different parts of the basin. For example, Ownbey and Kee (1967) reported that, at the time of their work, over half of the chloride load to the Detroit River could be attributed to industrial sources. Many chemical firms are, in fact, situated in the Detroit-Windsor area in order to use the inexpensive salt brine for the production of soda ash and other alkali products (Ownbey and Kee, 1967). In fact, Ownbey and Kee noted that Lake Erie's chloride level first began to increase at the turn of the century when these industries became established.

The influence of industrial sources of chloride is further illustrated by discharges to Onondaga Lake, a lake which drains into Lake Ontario via the Oswego River. Onondaga Lake has extremely high chloride concentrations (seasonal averages have exceeded 1500 mg/L), largely as a result of discharges from a chlor-alkali manufacturer (Effler et al., 1981). As will be discussed, the outflow from Onondaga Lake is a ajor reason for the extremely high chloride load to Lake Ontario from the Oswego River.

Atmospheric Sources

Chloride also enters the Great Lakes via rainfall. Atmospheric chloride inputs can be an appreciable part of the total load, particularly for Lakes Superior and Michigan which have large surface areas. The salt content of rainfall is largely derived from sea spray (Tiffany et al., 1969). Other means by which chloride could enter the atmosphere are by wind erosion of soil and industrial emissions. The significance of these sources is not known, however.

Minor Sources

Some minor sources of chloride to the Great Lakes include direct groundwater inputs, shoreline erosion and vessel discharges. The quantity of groundwater which directly flows into the lakes is not known, but is believed to be a small part of the water budget (Quinn, 1978). Consequently, chloride load from this source is assumed to be negligible.

Regarding shoreline erosion, which can contribute a large amount of particulate material to the Great Lakes (Monteith and Sonzogni, 1976), little information exists on chloride inputs. The Upper Lakes Reference Group (1977) did estimate a chloride load of about 800 metric tons per year from shoreline erosion, however. Since this is a small part of the total load (as will be shown), it will be ignored as a source.

Finally, the Upper Lakes Reference Group (1977) estimated that Lake Superior received a surprisingly high chloride load, about 11,000 metric tons per year, from vessel discharges (mostly salt water ballast). However, this source is likely only to be significant relative to other sources in Lake Superior, Lake Superior having the lowest total chloride load of any of the lakes. Vessel discharges are not considered further here as an important source.

Chloride Loads

Total Loads

Chloride loads to each of the Great Lakes are summarized in Table 1. These loads represent data primarily from the mid to late 1970's.

U.S. total tributary (river mouth) loads are the average annual load over the water years 1975 through 1978, except for Lake Erie, where data were not available for 1978. and Lake Michigan, where the 1975 load was excluded as a major shift in industrial chloride discharges occurred during this year. Calculations of chloride from gaged tributaries were made using the ratio estimator method (Great Lakes Water Quality Board, 1976; Sonzogni et al., 1978). This method accounts for the importance of flow variability in estimating annual loads. Chloride loads from ungaged and/or unmonitored tributaries were estimated as reported in Sonzogni et al. (1978). Primary sources of data included state surveillance programs, reports of the U.S. Geological Survey, the Upper Lakes Reference Group Study of the International Joint Commission, the U.S. Army Corps of Engineers Lake Erie

Table 1

Summary of Estimated
Chloride Loads to the Great Lakes
During the 1970's (mt/yr)

	Total Tributary	Direct Point Sources	Atmospheric	Input from Upstream Lake(s)
Lake Superior	195,900	32,600	55,000	
U.S.	89,500	3,200		
Canada	106,400	29,400		
Lake Michigan	598,000	220,400	82,900	
Lake Huron	583,400	23,200	48,700	477,700
U.S.	315,800	15,000		
Canada	267,600	8,200		
Lake Erie	741,100	170,000	20,100	2,759,000
U.S.	598,100	168,000		
Canada	143,000	2,000		
Lake Ontario	1,725,300	104,700	14,000	4,448,100
U.S.	1,365,800	23,300		
Canada	359,500	81,400		

Wastewater Management Study and other university studies and special state or federal projects. A more detailed description of the load calculation methodology and sources of data may be found in Sonzogni et al. (1978) and Sullivan et al. (1980).

U.S. direct point sources inputs were obtained or calculated from various sources. Direct inputs to Lake Superior and Lake Huron were based on data presented by the Upper Lakes Reference Group (1977). While this data represents information from the early to mid 1970's and thus may not reflect current conditions, inputs (with the possible exception of the direct point source chloride input to Lake Superior from Canada) are relatively small. Direct point source inputs to Lake Michigan were based on recent industrial loads supplied by the U.S. Environmental Protection Agency's Great Lakes National Program Office (H. Zar, U.S. EPA Region V, personal communication, 1980) and direct municipal inputs calculated from the total annual flow (average of 1975 and 1976 flows) discharged from all direct municipal dischargers and an assumed chloride effluent concentration of 160 mg/L. The use of 160 mg/L was based on the average effluent chloride concentration for Lake Erie basin municipal treatment plants as determined by the U.S. Army Corps of Engineer's Lake Erie Wastewater Management Study (reported in Sonzogni et al., 1978). Municipal direct point source inputs to Lake Michigan turned out to be about equal to industrial direct inputs. U.S. direct point source loads to Lakes Erie and Ontario were estimated similarly, except that no data on direct industrial chloride inputs were available. While these industrial inputs are not likely to be a major component of the total chloride budget to these lakes, there are a few industrial operations (e.g., steel plants) on the lake that could contribute substantial amounts of chloride and thus should be considered in future work.

Canadian tributary and direct point source loads to Lakes Superior and Huron are based on 1973 through 1975 data as reported by the Upper Lakes Reference Group (1977). Canadian total tributary and direct point source loads to Erie and Ontario are from Fraser and Wilson (1981) and Casey and Salbach (1974), respectively.

Atmospheric chloride inputs to each of the lakes were based on Andren et al. (1977). Inputs to Lake Huron from upstream lakes (Lakes Michigan and Superior) are from the Upper Lakes Reference Group (1977). The upstream lake contribution to Lake Erie is based on the average annual Detroit River load over the period 1975 through 1978 as supplied by the Michigan Department of Natural Resources (J. Hartig, Michigan Dept. of Natural Resources, personal communication, 1981). The upstream (Niagara River) input to Lake Ontario is the average of the 1975, 1976 and 1977 annual mean load reported by Chan (1979).

Inputs from Individual U.S. Tributaries

Chloride loads to each of the Great Lakes from selected major tributaries are presented in Table 2 for water years 1975 through 1978. Also included in these tables are the river mouth tributary flows. These data illustrate that large changes in year-to-year chloride loads are often closely related to changes in flow. Finally, the tables contain extrapolated total loads and flows for the whole basins. The methodology used for the load determinations were previously described. Similar information on other U.S. tributaries can be found in Sullivan et al. (1980).

Lake Superior. The largest U.S. contributer is the St. Louis River, which also has the largest flow. However, the load is high relative to the flow, indicating the likelihood of major industrial and municipal chloride

Table 2

Annual Mean Chloride Loads and Flows of Selected U.S. Great Lakes Tributaries for Water Years 1975 through 1976

	Chloride Load (mt/yr)				Flow at Mouth (m^3/s)			
River	1975	1976	1977	1978	1975	1976	1977	1978
Superior								
St. Louis	25468	14351	15617	25044	84.5	47.7	29.9	112.7
Nemadji	812	486	810	1125	12.9	10.3	7.7	15.1
Ontonagon	3697	3381	2435	4075	40.5	40.4	29.0	41.9
Carp	1362	1764	922	-	3.6	4.0	2.3	-
Mineral	21243	-	-	-	-	-	-	-
Total Tributary[a]	92680	81600	80220	104060	450.3	379.5	271.9	566.4
Michigan								
Menominee	3210	3970	5250	7800	100.8	95.6	58.8	94.6
Fox	51200	55700	36100	53200	118.4	124.2	58.1	121.6
Menomonee	10300	10800	5250	-	3.3	3.0	1.3	3.9
St. Joseph	78300	86800	68300	73100	123.0	143.4	96.1	135.9
Kalamazoo	60200	57000	48600	57000	68.4	67.1	44.1	52.8
Grand	171000	150000	95600	116000	162.4	185.4	73.2	102.5
Manistee	163000	85700	74900	71800	60.8	66.2	53.3	55.5
Manistique	4070	3900	2980	4200	61.2	58.3	48.0	76.0
Total Tributary[a]	775000	711600	490200	590300	1190.7	1276.0	732.0	1108.4
Huron								
Pine	1100	467	510	689	11.5	9.5	7.7	10.5
Au Sable	9926	10047	6900	7839	59.4	59.5	46.3	48.8
Au Gres	2974	3797	2465	3960	3.5	5.1	1.8	4.3
Saginaw	295140	320890	156433	202946	165.5	216.4	63.0	109.2
Total Tributary[a]	377400	422100	200600	263800	444.6	530.3	232.1	333.6

Table 2 (Continued)

River	Chloride Load (mt/yr) 1975	1976	1977	1978	Flow at Mouth (m^3/s) 1975	1976	1977	1978
Erie								
Clinton	-	44549	56100	-	-	26.7	13.6	-
Rouge	17724	-	73700	-	17.6	-	12.2	-
Maumee	273018	161000	123000	-	157.0	165.6	100.7	-
Sandusky	46846	25800	29400	-	39.8	29.8	24.3	-
Vermillion	4715	16149	5400	-	8.8	7.1	7.2	-
Cuyahoga	110964	132639	71000	-	50.5	39.2	28.3	-
Chagrin	21672	20944	15900	-	14.4	12.5	10.1	-
Total Tributary[a]	855600	696900	592200	-	608.3	615.0	422.9	-
Ontario								
Genesee	129819	129359	141060	213370	95.1	114.2	94.1	126.6
Oswego	1057788	1386606	965441	1160764	215.7	312.4	214.5	305.3
Black	7548	8606	10050	8537	137.0	194.1	161.9	168.8
Oswagatchie	4834	7348	5739	5382	75.2	125.5	100.1	112.6
Raquette	2481	3308	3106	4660	62.8	95.0	75.4	91.1
Total Tributary[a]	1197900	1607800	1166000	1489200	616.8	873.0	673.4	843.5

[a]Includes contributions from all U.S. tributaries, not just those listed; see Sonzogni _et al_. (1978) and Sullivan _et al_. (1980) for details.

contributions. The Carp River, which drains a portion of the upper peninsula of Michigan, also delivers a high chloride load relative to its flow. The Carp River receives considerable municipal inputs. Finally, the aptly named Mineral River delivers an extremely large chloride load relative to its flow. The large chloride load is apparently caused by the discharge of brine to the river from local mining operations (Sonzogni et al., 1978).

Lake Michigan. The largest single contributer of chloride was the Grand River, which drains into the eastern part of the lake. The Grand is also the largest (in terms of flow) of the Lake Michigan tributaries. Note that the Menomonee River, which drains a highly urbanized area within metropolitan Milwaukee, contributes a large load relative to its flow (Table 2). Road salt may have been a major contributer to this load. The Manistee River, which drains into eastern Lake Michigan, also contributes a large amount of chloride relative to its flow. Discharges to the river from salt mining operations account for the high load. The 1975 chloride load from the Manistee was particularly high relative to 1976, 1977 and 1978. Apparently, the reduced annual loads following 1975 reflect abatement of some industrial chloride discharges to the river. Notice that the major tributaries draining into the lower two-third of Michigan's eastern basin--namely, the St. Joseph, Kalamazoo, Grand, Muskegon and Manistee Rivers--contribute a large proportion of the total tributary chloride load to the lake.

Lake Huron. Most of the U.S. tributary inputs to Lake Huron is delivered to Saginaw Bay. The Saginaw River is the principal contributor to Saginaw Bay. The Au Gres River (which also drains into Saginaw Bay) also contributes a large load relative to its flow. High chloride loads to

Saginaw Bay reflect the influence of municipal and industrial sources. Most (over 90 percent) of the total U.S. wastewater flow to Lake Huron tributaries is delivered to streams draining into Saginaw Bay. Chemical industries and brine wells are also important sources of chloride to Saginaw Bay.

Lake Erie. In almost all cases, U.S. tributary chloride loads to Lake Erie tend to be high relative to flows (compared to tributaries with less developed watersheds). The Maumee River, the second largest U.S. tributary to the Great Lakes, ranks second behind Lake Ontario's Oswego River as the largest contributer (among tributaries) of chloride to the Great Lakes. Steel and manufacturing, as well as chemical industries, contribute to high chloride loads to streams draining the Detroit metropolitan area, such as the Clinton and Rouge Rivers. The Cuyahoga River, which drains the Cleveland area, also contributes a high chloride load relative to its flow. Overall, however, the largest input to Lake Erie, as seen from Table 1, is the input from the channel connecting it with Lake Huron, i.e., the Detroit River.

Lake Ontario. The tributary chloride load to Lake Ontario is dominated by the Oswego River (Table 2), the largest contributer of chloride of all the U.S. tributaries. While the Oswego has the largest historical annual mean flow of any U.S. tributary, its chloride load is also high relative to its flow. As discussed previously, a chlor-alkali plant on Onondaga Lake, which drains into the Oswego, is a major source of chloride to the Oswego. Overall, about 50 percent of the Oswego's chloride load has been attributed to point sources (Sonzogni et al., 1978). Despite the importance of the

Oswego as a chloride source, the largest overall input to Lake Ontario is the flow from the upper lakes through the Niagara River.

Deicing Salt Useage Versus Loads

While it is not possible to directly assess the amount of road salt that reaches the Great Lakes, some insight on the important of road salts can be obtained by comparing application rates with the total chloride loads given in Table 3. Based on PLUARG (1977), the amount of road salt applied annually to basins of Superior, Michigan, Huron, Erie and Ontario total 88,000, 595,000, 370,000, 696,000, and 1,046,000 metric tons, respectively. Accordingly, even if all applied reached the lakes (which is not the case), road salt would account for less than 35 percent of the load for all lakes except Michigan. In the case of Lake Michigan, the higher ratio of road salt applied to total load is perhaps the result of an overestimate of the road salt applied. Apparently, in determining salt useage for Lake Michigan, PLUARG (1977) estimates were made on a county basis. However, because large portions of counties adjacent to southern Lake Michigan (these counties are heavily populated and presumedly have high salt useage) do not drain into the lake, salt useage in the Michigan drainage basin may have been overestimated.

Thus, it appears that road salt contributes a significant, but not necessarily a predominant, portion of the anthropogenic chloride load to Great Lakes. This conclusion is consistent with the results of a study of chloride inputs from the City of Buffalo (Meredith and Rumer, 1976), which indicated that road salts were the source of 36 percent of the chloride leaving Buffalo's combined sewer system.

Table 3

Comparison of Estimates of Chloride Loads (metric tons/year) to the Great Lakes

Lake	Estimated Load for 1960 (O'Connor & Mueller, 1970)	Estimated Load for the mid to late 1970's (Present Study)
Superior	230,000	283,500
Michigan	927,000	901,300
Huron	1,417,000	1,133,000
Erie	4,619,000	3,690,200
Ontario	5,944,000	6,292,100

Comparison of Present Chloride Load Estimates With Previous Estimates

In their now classic water quality modeling paper, O'Connor and Mueller (1970) estimated 1960 chloride loads for the entire Great Lakes system. Their estimated chloride loads to each of the Great Lakes are compared with the loads from this study (mid to late 1970's) in Table 3. O'Connor and Mueller's chloride load includes an "other sources" category, which was determined by difference (so that inputs balanced storage and outputs). These "other sources" comprised 22, 23, 48, 17 and 21 percent of O'Connor and Mueller's loads presented in Table 3 for Lakes Superior, Michigan, Huron, Erie and Ontario, respectively. Thus, were it not for their "other sources," O'Connor and Mueller's loads would be considerably less than those of this study for all lakes except Erie.

Ownbey and Kee (1976) presented an assessment of chloride loads from individual tributaries to Lake Erie. Their results are compared to estimates from this study in Table 4. Note that in most cases current estimates are greater than Ownbey and Kee's.

The estimates of both O'Connor and Muller (1970) and Ownbey and Kee (1967) were necessarily based on scant data. In many cases, loads were derived from unit area loads or per capita inputs rather than actual measurements. Loads from the present study are based on better information and likely are more accurate. For example, loads to Lake Erie were based on extensive monitoring of streams, especially during the high flow events when a large portion of the total load may enter the lakes, as part of the Lake Erie Wastewater Management Study (U.S. Army Corps of Engineers, 1979).

Table 4

Comparison of Estimates of Chloride Loads (metric ton/year) to Lake Erie

	Ownbey and Kee (1967)	Present Study[a]
Detroit River	2,996,400	2,759,000
Huron "	14,982	25,650
Raisin "	20,884	29,687
Moumee "	118,040	185,673
Portage "	5,448	11,542
Sandusky "	29,510	34,015
Black "	7,264	16,737
Rocky "	19,068	10,800
Cuyahoga "	72,640	104,701
Chagrin "	4,540	19,339
Grant " (Ohio)	635,600	
Ashtabula	9,080	4,553
Conneant	2,724	4,498
U.S. Direct Municipal Discharges	49,940	143,000

[a]Average of annual mean load for 1975, 1976 and 1977; (in some cases loads were available for two or in one case one year); direct municipal discharges based on average of 1975 and 1976 flows and an assumed effluent concentration of 160 mg/L chloride.

Long-Term Trends in Chloride Loads and In-Lake Concentrations

While not obvious from the comparison of current loads with 1960 loads (Table 3), there is evidence that some chloride inputs have decreased, especially industrial inputs. As early as 1972, considerable progress was made in controlling certain Michigan point sources of chloride. For instance, the U.S. Environmental Protection Agency (1972) reported that a 40 percent reduction in the chloride discharge of several major industries would occur between 1971 and January 1973. As mentioned previously, a significant decrease in the chloride load of Michigan's Manistee River, which received chloride from major salt producers, is attributed to abatement measures (Little, G., Michigan Department of Natural Resources, personal communication). Perhaps the best example of decreasing chloride loads is the Detroit River contribution to Lake Erie. Figure 1 shows how the chloride load has steadily decreased since the late 1960's. This decrease is most likely the result of reduced industrial chloride discharges. Further, comparing the concentration of chlorides at the head of the Detroit River with those at the mouth (Table 5) suggests that the reduced Detroit River load is the result of decreased inputs from the Detroit-Windsor complex. While the concentration of chloride at the head of the Detroit River has changed little over the period of record, the concentration at the Detroit River mouth has progressively decreased. This indicates that the observed decrease is probably the result of reduced chloride discharges, most likely from industrial sources from the Detroit-Windsor area.

Table 6 shows typical average concentrations (open lake) that were measured during the early 1900's, the 1960's and 1970's. While concentrations have apparently increased significantly since 1900, the changes

Table 5

Comparison of Annual Mean Chloride Concentrations (mg/L)

at the Head and Mouth of the Detroit River[a]

Water Year	Head	Mouth
1967	9	-
1968	10	23
1969	11	18
1970	10	18
1971	9	15
1972	9	17
1973	9	14
1974	9	16
1975	9	15

[a]Data from Great Lakes Water Quality Board (1976)

Table 6

Changes in Great Lakes Chloride Concentrations (mg/L)

(values from Beeton, 1969, except as noted)

	1900's	1960's	Current
Lake Superior	1.2	1	1[a]
Lake Michigan	3	6-7	7.7[b]
Lake Huron	5	7	5.5[a]
Lake Erie	11	26[c]	20[d]
Lake Ontario	10	27[c]	27.7[e]

[a]Upper Lakes Reference Group (1977)

[b]Rockwell et al (1981)

[c]Weiler and Chawla (1969)

[d]Rockwell, D.C., U.S. EPA, Great Lakes National Program Office, Chicago personal communication, 1981)

[e]Simons (1979)

between the 1960's, when chloride inputs from industrial sources were likely at their peak, and the present are not as obvious. In fact, current concentrations of chloride in Lake Erie appear to be less than reported for the 1960's. This may be an indication of decreased chloride loads to Lake Erie. Further, because Lake Erie is much shallower than the other lakes it flushes more quickly. Hence, a decrease in chloride concentration as a result of decreased chloride loads would be noticed in Lake Erie much faster than in the other Great Lakes.

Accordingly, it would appear that, at least in some locations, industrial chloride inputs are decreasing. On the other hand, new industrial operations, such as new plants or new treatment technologies, could increase inputs. For example, a new wastewater treatment plant for the steel industry, located near Gary, Indiana, is expected to increase its chloride input to Lake Michigan by 49,800 metric tons per year (University of Michigan Research News, 1978). Further, as mentioned previously, municipalities may be discharging more chloride than previously with the use of metal salts for phosphorus removal. More information is needed on individual point source contributions to evaluate overall trends of chloride inputs to the Great Lakes.

Chloride Model of the Great Lakes

Several investigators have presented models relating chloride inputs to chloride concentrations in the Great Lakes. The chloride model of O'Connor and Mueller (1970) is particularly noteworthy, as it considered the Great Lakes as an integrated system. Snow (1974) applied O'Connor and Mueller's approach specifically to Lake Michigan. Meredith et al. (1974) and

Richardson (1974) applied the same basic model approach to Lake Erie and Saginaw Bay, respectively. Other modeling attempts similar to O'Connor and Mueller's include those of Rainy (1967), Dingman and Johnson (1971), and Butler et al. (1974).

A chloride simulation (CS) model similar to that developed by O'Connor and Mueller (1970) is used here to reevaluate predictions of future chloride concentrations using current loading information. Importantly, the model considers the effect of changes to one lake on another by treating the lakes as five completely mixed systems in series. The model is used to examine Lake Michigan in detail because of current concern over the effects of chlorides and other dissolved solids in the lake.

Model Formulation

The CS model is based on a simple chloride mass balance which reflects the conservative behavior of chloride. The change in chloride concentration as a function of time is thus represented as the sum of inputs minus the outputs, expressed mathematically as:

$$V \frac{dc}{dt} = \Sigma W - QC \tag{1}$$

where,

C = in-lake chloride concentration

V = lake volume

ΣW = sum of all chloride loads, including those from upstream lakes

Q = flow out of the lake

t = time

Equation 1 can be solved analytically, yielding:

$$C(t) = \frac{\Sigma W}{Q} (1-e^{-\frac{Q}{V}t}) + C_o e^{-\frac{Q}{V}t} \qquad (2)$$

where,

$C(t)$ = Chloride concentration at time t

Co = Initial chloride concentration, when t = 0

Equation (2) also shows that following a change in the chloride loading, equilibrium or steady state conditions are approached exponentially. At steady-state ($t = \infty$), $C = \frac{\Sigma W}{Q}$. That is, at steady-state the in-lake concentration equals the average concentration of the inflow. Approximately 95% of the steady-state concentration is obtained within three hydraulic residence times, the hydraulic residence time defined as $\frac{V}{Q}$. For detail on basic model formulation, including elaboration on treating the lakes in series, see O'Connor and Mueller (1970) and Chapra and Sonzogni (1979).

Model Inputs

Chloride inputs for the CS model were those summarized in Table 3. For lake volumes and flows, values reported in O'Connor and Mueller (1970) were used except in the case of Lake Michigan where data summarized in Rodgers and Salisbury (1981) was used. Lake Michigan hydrology is complicated by the difficulty of measuring flows out through the Straits of Mackinac. Consequently, outflows from Lake Michigan must be calculated indirectly using a water budget procedure (Quinn, 1977).

Table 7 compares water budgets from three sources, including the Rodgers and Salisbury (1981) budget used here. The tributary discharge in Rodgers

Table 7

Water Budgets for Lake Michigan

(m^3/yr)

	O'Conner and Mueller (1970)	Quinn (1977)[a]	Rodgers and Salisbury (1981)
Tributary Discharge	34.8×10^9	33.0×10^9	32.3×10^9
Net Precipitation (Preceiptation-Evaporation)	14.3×10^9	6.3×10^9	12.5×10^9
Infiltration	-	-	0.4×10^9
Storage	0	0.4×10^9	0
Outflow through Chicago Diversion Canal	2.8×10^9	2.9×10^9	2.9×10^9
Outflow through Straits of Mackinaw	46.3×10^9	36.0×10^9 (70.8×10^9[b])	42.3×10^9
Volume (km3)	4877	4915	4976
Water Residence Time (yrs)	99	126 (67[b])	110

[a]Average over 1950-1966

[b]Assumes return flow during stratified period

and Salisbury is based on long-term historical flows recently reported by Sonzogni et al. (1979) and Sullivan et al. (1980).

Note in Table 7 that Quinn (1977) reports two possible hydraulic residence times. The shorter estimate, 67 years, incorporates a return flow through the straits during summer stratification (based on limited measurements of currents in the straits). The inclusion of the deep layer return flow when calculating the hydraulic residence time or as a source of loading presupposes that these waters are completely mixed throughout Lake Michigan. There is some evidence that this is not case, and that the return flow creates only a localized cell of mixing. For instance, Moll et al. (1976), using cluster analysis of chemical and biological parameters, were able to identify Lake Michigan waters in a plume extending into Lake Huron, but Lake Huron waters could not be located west of Bois Blanc Island (Lake Huron). Chloride data from Lake Michigan during 1962-63 and 1976, as reported in Rockwell et al. (1980), indicates a sharp gradient in the area adjacent to the straits as compared to the rest of Lake Michigan. Consequently, hydraulic residence times on the order of 100 years appear to be most representative for chloride modeling purposes.

Model Results

Figure 2 depicts the chloride concentrations changes in each of the Great Lakes will change over time given that current loads to the Great Lakes System (Table 1) remain the same. Projected long-term steady-state concentrations range from about 4 mg/L in Lake Superior to about 30 mg/L in Lake Ontario. The greatest chloride concentration change is expected to occur in Lake Michigan, where the current level of 7.7 mg/L is projected to rise to nearly 20 mg/L over the next 300 years.

Figure 2 also indicates a relatively small rise of chloride in Lake Erie. This increase is mostly in response to the gradual build-up of chloride in the upper lakes, which drain into Lake Erie. The initial dip in concentration in Lake Ontario in Figure 2 reflects a lagged response to changes in chloride concentrations in Lake Erie. Both Lakes Erie and Ontario are presently close to being in equilibrium with their loads, and in fact the present Lake Ontario chloride concentration appears to still be equilibrating to decreasing Lake Erie chloride concentrations during the recent past. Thus, assuming current loads to the system remain the same, chloride in the lower lakes will increase slightly as a result of the buildup of chloride in the upper lakes according to the CS model.

Table 8 shows the reductions in external chloride loads that would be needed to maintain current chloride levels in the lakes (initial conditions in Figure 2). Reductions assume that upstream lakes maintain current conditions. For instance, to maintain a concentration of 5.5 mg/L, Lake Huron would require a 32 percent reduction in its external chloride load provided Lake Michigan and Lake Superior remained at their present concentrations of 1.0 and 7.7 mg/L, respectively. Note that to maintain present levels in Lake Michigan, a large reduction in the current load will be required. Also, while Table 8 shows a large percent reduction in the chloride load to Lake Superior would be required to maintain the very low current chloride concentration of 1 mg/L, the actual load reduction required is relatively small.

Examining Lake Michigan in more detail, Figure 3 illustrates a range of possible equilibrium chloride concentrations bounded by upper and lower estimates of the current chloride load and hydraulic residence times. A $\pm$ 25

Table 8

Reduction in External Chloride Load Required

to Maintain Current Concentrations

Lake	% of present External Load	MT/YR Reduction
Superior	77	218,400
Michigan	60	540,800
Huron	32	209,700
Erie	8	226,200
Ontario	0	0

percent range for the chloride load was chosen, reflecting an approximate error bounds in chloride loading estimates. Ranges in hydraulic residence times were deduced from Table 7, and reflect the uncertainty in outflow from Lake Michigan.

Notice in Figure 3 that to achieve an equilibrium concentration below the current concentration, the current load to Lake Michigan would have to be reduced by a factor of 2 or more even under the most optimistic (shortest) hydraulic residence time. From a Lake Michigan management perspective, then, it is clear that Lake Michigan chloride concentrations are likely to continue to build-up, even under conservative estimates of current loading and hydraulic residence times. Subsequently, Lake Michigan's chloride build-up will affect Lakes Huron, Erie and Ontario.

A relevant question is whether the response time to a Lake Michigan load reduction could be shortened. For example, what chloride load reduction to Lake Michigan could achieve a desired in-lake chloride concentration in 30 years as opposed to the normal response time of 300 years. In order to reduce the time required to reach a target concentration, it can be shown from a reformulation of equation 2 that the chloride load would have to be reduced to a greater extent than if the time of response was not a criterion. In other words, to achieve a 50 percent reduction in the chloride concentration of Lake Michigan at an accelerated pace, the load reduction would necessarily have to be greater than 50 percent until the target concentration was obtained. Accordingly, in lakes with long hydraulic residence times such as the Great Lakes, the long-term consequence of allowing conservative substances to exceed prudent limits should be realized in advance and long-term planning made accordingly. Managers should therefore realize that recovery periods for conservative ions will be more prolonged or require accentuated levels of treatment as compared to nutrients which are subject to losses other than natural flushing (i.e., sedimentation).

Management Considerations

The CS model results (Figure 2) indicate that the chloride concentration in Lake Michigan, and to a lesser extent Lake Huron, may be expected to increase most dramatically in the future. For Lake Michigan, concentrations are expected to increase to about 20 mg/L, an increase of greater than 6 fold compared to concentrations at the turn of the century. A salient management question, then, is whether the Lake Michigan ecosystem will be seriously degraded by the chloride change.

Storemer (1978) provides evidence that the less desirable phytoplankton species that have invaded the Great Lakes tend to come, virtually exclusively, from saline waters. The filamentous blue green alga, _Stephanodiscus_, which has been known to decrease filtration time at water treatment plants as well as cause taste and odor problems, has already been observed to be increasingly more prevalent in southern Lake Michigan (where industrial chloride discharges are high). The rapid spread through the Great Lakes of the marine alga, _Bangia atropurpurea_, is believed to be linked to increased chloride levels or increases in dissolved solids. _Eureytemora affinis_, a brackish water copepod, is also now established in the Great Lakes. Stoermer (as noted in Great Lakes Water Quality Board, 1977) has further hypothesized that a biological breakpoint between 7.5 and 10 mg/L chloride may exist for Lake Michigan. Beyond this concentration, a major shift in phytoplankton toward nuisance taste and odor causing blue green algae could occur.

There is also some evidence that, in general, productivity increases with increases in chloride or total dissolved solids (Rawson, 1951, 1960; Northcote and Larkin, 1956; Kerekes and Nursall, 1966; Seenayga, 1973). Robertson and Powers (1967) reported that total organic matter in the Great Lakes increased in the order of Superior, Huron, Michigan, Erie and Ontario. Average chloride concentrations also increase in the same order. Stoermer (1978) has thus questioned whether nutrient control alone will provide desired improvements (less eutrophic) in Great Lakes water quality, which is often measured in terms of the assembleges of organisms. However, as discussed by Sorrenson et al. (1978) and Stoermer (1978), the effects of chlorides or other dissolved solids are subtle, are often confounded by other factors (e.g., nutrient enrichment) and are difficult to directly evaluate experimentally.

Despite the difficulty in directly assessing whether increasing chloride levels will seriously impair Lake Michigan, some inferences may be obtained from other lakes with higher chloride levels. For example, Lake Ontario's average chloride concentration currently is about four times higher than found in Lake Michigan. Lake Ontario's Irondequoit Bay has chloride concentrations several times Lake Ontario's and Onondaga Lake has even higher chloride levels.

Undoubtedly, the Lake Ontario ecosystem has been severely disturbed. Stoermer et al. (1975) reported that Lake Ontario's phytoplankton assemblage is dominated by species indicative of degraded water quality, including species of blue-green algae that are potential nuisances. They note that many of the taxa commonly found in the offshore waters of the more oligotrophic upper Great Lakes are absent or rare in Lake Ontario. Finally, they report a shrinking abundance of halophilic species in the lake, such that the dominant and sub-dominant taxa are more commonly found in brackish and saline inland waters.

Although these changes indicate degraded water quality, it is not clear what impact this has had on uses of the lake. Little information exists on the economic impacts of these changes or how human perception of the quality of water has changes. Lake Ontario is supporting a growing sport fishery and is still a major source or drinking water. Thus, while Lake Ontario has undergone extensive ecological changes, the ecosystem still serves many uses. Accordingly, it is difficult to quantify the practical impact that would result should some of the changes observed in Lake Ontario become manifested in Lake Michigan.

If an effect of chloride or increased dissolved solids were to be obvious, it should be so in Onondaga Lake and Irondequoit Bay, where chloride levels have gotten extremely high. Interestingly, the high salinity of Onondaga Lake has not resulted in significant amounts of non-fresh water organisms at any trophic level (Effler et al., 1981). Irondequoit Bay was reported to have phytoplankton species and numbers similar to Onondaga Lake. Both of these waters are productive, however, and receive large nutrient inputs.

In summary, analogies to other lakes where chloride levels have increased provides conflicting inferences as to the future of Lake Michigan. It may well be that the influence of conservative ions is secondary to nutrient enrichment. For example, while higher conservative ion levels may provide a competitive advantage for halophilic species, they may not flourish without abundant nutrient supplies. In other words, increased conservative ion levels may be a factor ecologically, but of lesser importance than other factors such as nutrients.

The occurrence of halophilic organisms in the Great Lakes as opposed to other inland lakes with high chloride levels may also be related to the direct linkage of the Great Lakes with the sea. With the construction of St. Lawrence Seaway system, salt water organisms have had access to all the Great Lakes. The invasion of non-native fish in this manner (for example, the sea lamprey and alewife) is well documented. Further, ocean going vessels using the Great Lakes often dump salt water ballast into the lakes.

The uncertainty of the effect of conservative ions exemplifies the need to carefully monitor how the Great Lakes respond to the massive municipal point source phosphorus control program enacted during the 1970's. As discussed in Heidtke et al. (1979), future phosphorus loads to the Great Lakes from municipal point sources should be reduced over 50 percent (750 metric tons/year) compared to mid-1970 levels. The extent to which the lakes actually respond to this reduction should provide valuable insight into the importance of conservative ions as a pollutant and the potential need for controlling chloride inputs to the Great Lakes, especially Lake Michigan.

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List of Figures

Figure 1. Annual Mean Chloride Loads (and their standard deviation) to Lake Erie from the Detroit River (Michigan Department of Natural Resources data based on monthly measurements at ten stations across river).

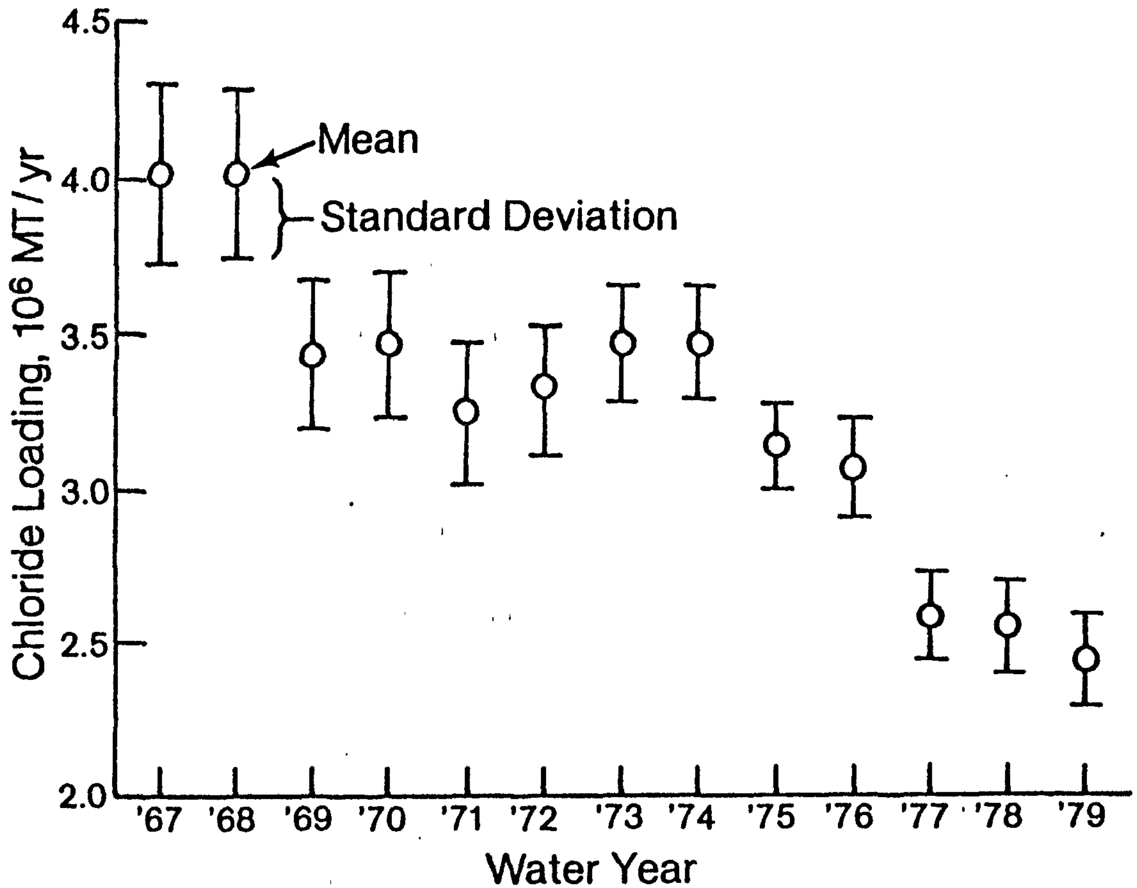
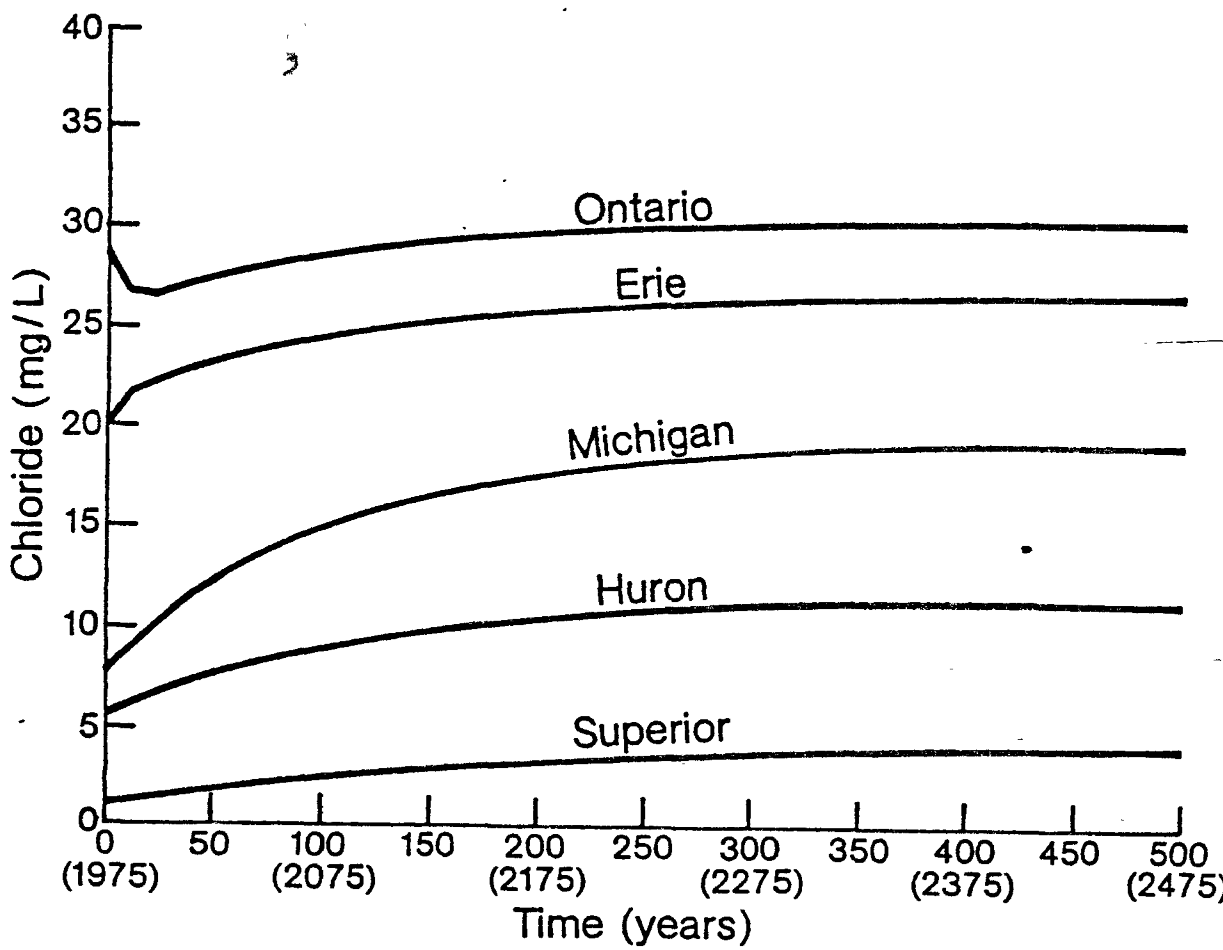


Figure 2. Projections of Chloride Concentration Over Time in Response to Current External Loads.



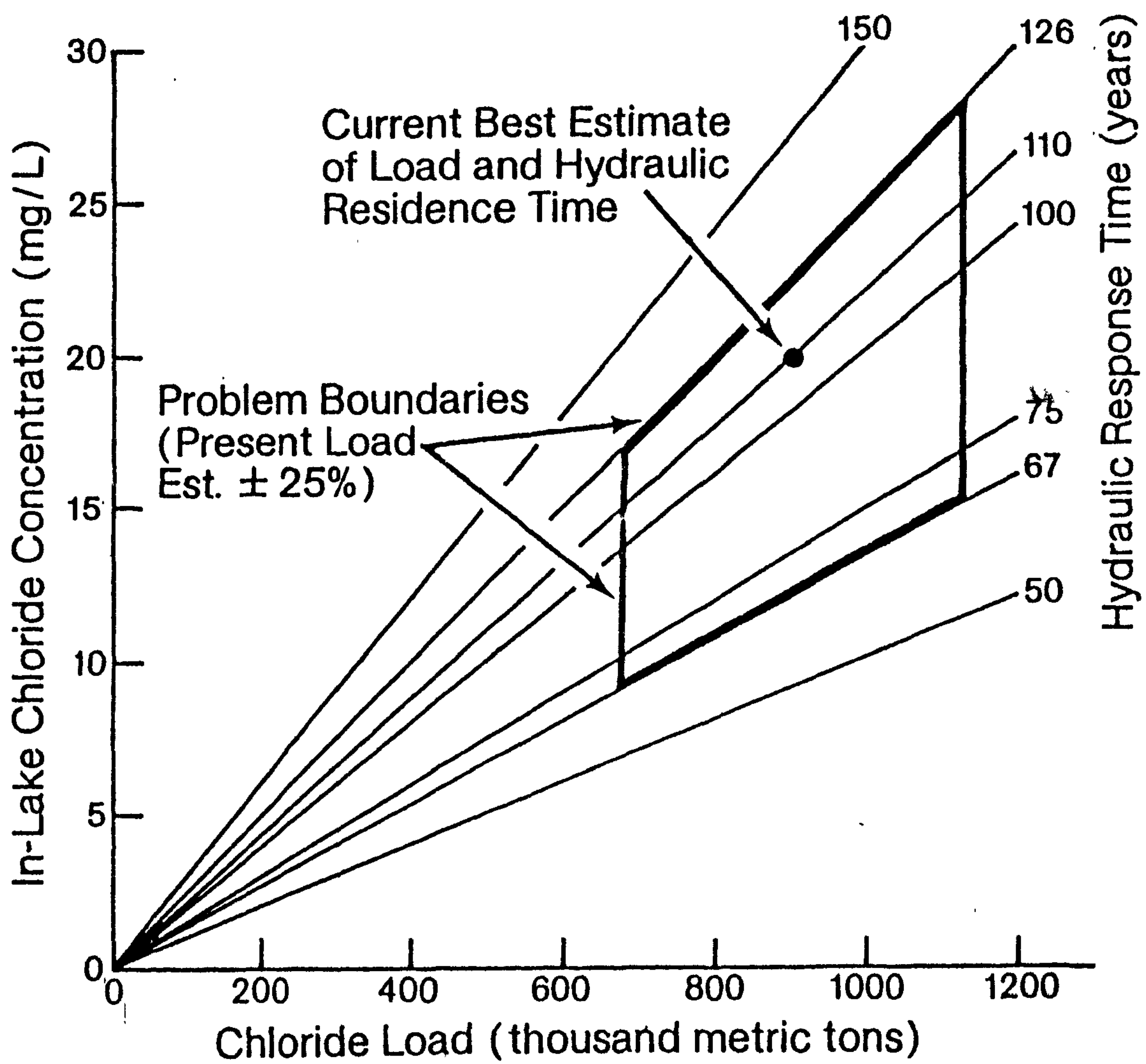


Figure 3. Lake Michigan Chloride Load Versus Equilibrium Chloride Concentration for a Range of Possible Hydraulic Detention Times.